Paper reference
Applied methods
Main advancement and results
Limitations

Contrail-related papers of S. Unterstrasser and how they depend on each other

All core papers (any paper in a coloured box) address how contrails evolve over time and highlight sensitivities to atmospheric and aircraft parameters. They are based on the LES-model EULAG with a fully coupled ice microphysics code. With this setup, idealised atmospheric scenarios are prescribed.

Simulation of contrail formation in the expanding jet

Simulation of young contrails and their interaction with the wake vortices

Simulation of contrail-cirrus and natural cirrus

Advancing the particle-based ice microphysics model LCM

Further papers based on output of a core paper

List of symbols:
Cruise temperature T^*
Background humidity RH_i^*
Vertical wind shear s
Ice crystal size distribution SD
Spatial SD initialisation SI
Width of SD r_{SD}
Wake vortex strength Γ
Brunt-Väisala frequency N_{BV}
Eddy-dissipation rate ε
Wing span b

#1 Unterstrasser et al, MZ, 2008
2D simulation with EULAG-BULK
- Strong dependence of ice crystal loss on ambient temperature and humidity.
- Tested sensitivities: [T^*, RH_i^*, N_{BV}, ε, Γ, EI_{ice}]

#4 Unterstrasser & Sölch, ACP, 2010
2D simulation with EULAG-LCM
Improved ice micrcophysics
- Repeat sensitivity studies of 2008-paper, increase parameter range
- Demonstrate superiority of LCM (improves #1)
- Prescribed r_{SD} affects crystal loss
- Initial ice crystal numbers are reduced during vortex phase
- Tested sens: [T^*, RH_i^*, r_{SD}, EI_{ice}]

#5 Unterstrasser et al, ACP, 2014
3D simulation with EULAG-LCM
Only passive tracer considered
- Focus on dynamical processes
- Investigate the re-distribution of a passive exhaust tracer
- Wake vortex induced heterogeneity
- Comarison with NTMIX model and in-situ measurements
- Tested sens: N_{BV}, ε, Γ, s, SI

#7 Unterstrasser, JGR, 2014
3D simulation with EULAG-LCM
- Focus on microphysical processes
- Demonstrate superiority of 3D vortex dynamics also for contrail microphysics (improves #1, #2)
- Demonstrate importance of vortex-phase processes for later contrail-cirrus properties
- Hollow contrail: crystal inertia?
- Tested sens: T^*, RH_i^*, r_{SD}, EI_{ice}, m_f, SI

#8 Unterstrasser & Görsch, JGR, 2014
3D simulation with EULAG-LCM
- Variation of aircraft type (#1, #4, #5, #7 used a large generic aircraft) accounting for changes in m_f, b and Γ
- Vortex phase: Smaller aircraft → shallower contrail and less ice crystal loss
- AC type leaves long-lasting signal in contrail-cirrus properties
- Tested sens: RH_i^*, EI_{ice}, N_{BV}, SI

Gruber et al, ACP, 2018:
Regional simulation with COSMO-ART
- Impact of contrails on photovoltaic power production
- Early ice crystal loss affects contrail-cirrus properties on a regional scale

#9 Unterstrasser, ACP, 2016
3D simulation with EULAG-LCM
- Summarizes the impact of T, RH_i^*, EI_{ice} and AC type on early contrail properties
- Parametrization for ice crystal loss, contrail height and width after vortex break-up is derived; allows refined contrail initialisation in a large-scale models
- Consideration of vortex phase processes reduces the biofuels effect on ice crystal number
- Comparison of four LES models

Forster et al, JAS, 2012:
- Computes radiative forcing of single contrail-cirrus scenes
- Differences between ICA and full 3D radiatiave transfer computation

Kärcher et al, ACP, 2009:
Derives PDFs of contrail properties based on a Monte-Carlo application of a simplied contrail-cirrus model

#2 Unterstrasser & Gierens, ACP, 2010a (Part 1) **#3** Unterstrasser & Gierens, 2010b (Part 2)
2D simulation with EULAG-BULK
- First systematic study of contrail-cirrus transition
- Investigates contrail spreading over 6 hours
- Analyses geometric, optical and microphyisal contrail quantities
- Time-constant background humidity and temperature

Part 1
- Investigate main parameters: vertical wind shear, ambient temperature and humidity.

Part 2
- Impact of radiation on contrail evolution
- Sensitivity of contrail-cirrus properties to ice mass and crystal number of young contrails
- Potential of re-nucleation of soot cores released during vortex phase sublimation

#11 Unterstrasser et al, MZ, 2017a (Part 1) **#12** Unterstrasser et al, 2017b (Part 2)
2D simulation with EULAG-LCM
- Investigates evolution of contrail-cirrus (CC) and natural cirrus (NC) over 10 hours
- Analyses geometric, optical and microphysical cloud quantities of CC and NC
- Different updraught scenarios with time-varying background humidity and temperature

Part 1
- Separate simulations of CC and NC
- Investigate their (different) response to a change in the updraught scenario: Weak, but enduring updraughts allow for the longest CC life times. For NC, the updraught speed is crucial.
- Despite their different formation mechanisms (contrails are generated locally and have initially much higher ice crystal number concentrations than natural cirrus) it is not possible single out microphysical criteria that could help to distinguish in general between both cloud types in observations.

Part 2
- Interaction of CC and NC simulated
- CC becoming embedded in NC do not generally remain identifiable as such in observations.
- At some point, NC ice crystals exist in large parts of CC → strong local co-existence of CC and NC ice crystals. No separation into natural and anthropogenic cloud possible/meaningful.
- Advanced analysis: CC properties are computed with and without considering the co-existing NC ice crystals which aids the interpretation of potentially "contaminated" CC observations.

#13 Unterstrasser & Stephan, AJ, 2020
3D simulation with EULAG-LCM
- Formation flight scenarios
- Four-vortex dynamics is complex
- Chaotic dependence on lateral and vertical offset of the two involved aircraft
- After vortex break up, formation flight contrails are less deep, but broader than „single aircraft" contrails

#15 Unterstrasser, Aerospace, 2020
2D simulation with EULAG-LCM
- Compare evolution of contrail-cirrus produced by a single aircraft and by a formation
- Strong saturation effects in the formation flight scenario → large contrail mitigation potential

Dahlmann et al, Aerospace, 2020 and Marks et al, Aerospace, 2021:
Non-linear climate response model AirClim extended to account for saturation effects due to formation flight. Flight inventories created
- Global climate assessment of formation flight
- Decrease of fuel consumption by 5%
- Climate impact reduced in average by 24% (mainly due to overlapping contrails)

#6 Unterstrasser & Sölch, 2014
Box model and 2D simulations with EULAG-LCM
- Adaptive control of simulation particle (SIP) number
- Stochastic nucleation implementation drastically reduces the number of required SIPs
- The number of SIPs required for convergence is generally fairly low

#10 Unterstrasser et al, 2017
Box model simulations of particle-based collisional growth
- Three published algorithms were rigourously tested; one algorithm is superior
- Golovin, Long and Hall kernels tested
- SIP ensemble properties are crucial for algorithm performance.

#14 Unterstrasser et al, 2020
Column model simulations of particle-based collisional growth
- Processes: Collisional growth + sedimentation
- AON algorithm tested
- The number of SIPs required for convergence is lower than anticipated from previous box model
- Even though particle-based methods use a better suited process description (stochastic master vs. deterministic Smoluchowski equation), results are similar to traditional bin microphysical models.

Peer-reviewed articles

2020

Dahlmann, K., Matthes, S., Yamashita, H., **Unterstrasser, S.** , Grewe, V., Marks, T.: Assessing the Climate Impact of Formation Flights, *Aerospace* **7(12)**, 172 Article (open-access)

#15 Unterstrasser, S. : The contrail mitigation potential of aircraft formation flight derived from high-resolution simulations, *Aerospace* **7(12)**, 170 Article (open-access)

#14 Unterstrasser, S. , F. Hoffmann, M. Lerch: Collisional growth in a particle-based cloud microphysical model: insights from column model simulations using LCM1D (v1.0) *Geosci. Model Dev.* **13**, 5119-5145, doi:10.5194/gmd-13-5119-2020 Article (open-access)

#13 Unterstrasser, S. , A. Stephan: Far field wake vortex evolution of two aircraft formation flight and implications on young contrails, *The Aeronautical Journal*, 124, 667-702 Article (open-access)

2018

Gruber, S., **S. Unterstrasser**, J. Bechtold, H. Vogel, M. Jung, H. Pak, B. Vogel: Contrails and their impact on shortwave radiation and photovoltaic power production - A regional model study, *Atmos. Chem. Phys.*, 18, 6393-6411 Article (open-access)

2017

#12 Unterstrasser, S., K. Gierens, I. Sölch, M. Wirth: Numerical simulations of homogeneously nucleated natural cirrus and contrail-cirrus. Part 2: Interaction on local scale, *Meteorol. Z.*, 26, 643-661 Article (open-access)

#11 Unterstrasser, S., K. Gierens, I. Sölch, M. Lainer: Numerical simulations of homogeneously nucleated natural cirrus and contrail-cirrus. Part 1: How different are they?, *Meteorol. Z.*, 26, 621-642 Article (open-access)

Grewe, V., Bock, L., Burkhardt, U., Dahlmann, K., Gierens, K., Hüttenhofer, L., **Unterstrasser, S.**, Rao, A. G., Bhat, A., Yin, F., Reichel, T, G., Paschereit, O., Levy, Y.: Assessing the climate impact of the AHEAD multi-fuel blended wing body, *Meteorol. Z.*, 26, 711-725 Article (open-access)

#10 Unterstrasser, S., F. Hoffmann, M. Lerch: Collection/aggregation algorithms in Lagrangian cloud microphysical models: Rigorous evaluation in box model simulations, *Geosci. Model Dev.*, **10**, 1521-1548, doi:10.5194/gmd-10-1521-2017 Article (open-access)

2016

#9 Unterstrasser, S.: Properties of young contrails - a parametrisation based on large eddy simulations, *Atmos. Chem. Phys.*, **16**, 2713-2733 Article (open-access)

2014

#8 Unterstrasser, S. and N. Görsch: Aircraft-type dependency of contrail evolution, *J. Geophys. Res. Atmos.*, **119**, 14015-14027, doi:10.1002/2014JD022642 Abstract

#7 Unterstrasser, S. : Large-eddy simulation study of contrail microphysics and geometry during the vortex phase and consequences on contrail-to-cirrus transition, *J. Geophys. Res. Atmos.*, **119**, 7537-7555, doi:10.1002/2013JD021418 Abstract

#6 Unterstrasser, S. , I. Sölch: Optimisation of the simulation particle number in a Lagrangian ice microphysical model, *Geosci. Model Dev.*, **7**, 695-709 Article (open-access)

#5 Unterstrasser, S., R. Paoli, I. Sölch, C. Kühnlein, T. Gerz: Dimension of aircraft exhaust plumes at cruise conditions: effect of wake vortices, *Atmos. Chem. Phys.* , **14**, 2713-2733 Article (open-access)

2012

Forster, L., C. Emde, **S. Unterstrasser** , B. Mayer: Effects of three-dimensional photon transport on the radiative forcing of realistic contrails, *Journal of Atmospheric Science*, **69**, 2243-2255 Article
The original article appeared with an incorrect author list. The corrected version is given in a Corrigendum

2010

#4 Unterstrasser, S. und I. Sölch: Study of contrail microphysics in the vortex phase with a Lagrangian particle tracking model, *Atmos. Chem. Phys.*, **10**, 10003-10015 Article (open-access)
In the original version a figure was incorrectly displayed due to errors in the typesetting process. The correctly displayed figure is shown here

#3 Unterstrasser, S. und K. Gierens: Numerical simulations of contrail-to-cirrus transition - Part 2: Impact of initial ice crystal number, radiation, stratification, secondary nucleation and layer depth, *Atmospheric Chemistry and Physics*, **10**, 2037-2051 Article (open-access)

#2 Unterstrasser, S. und K. Gierens: Numerical simulations of contrail-to-cirrus transition - Part 1: An extensive parametric study, *Atmospheric Chemistry and Physics*, **10**, 2017-2036 Article (open-access)

2009

Kärcher, B., U. Burkhardt, **S. Unterstrasser** und P. Minnis: Factors controlling contrail cirrus optical depth, *Atmospheric Chemistry and Physics*, **9**, 6229-6254 Article (open-access)

2008

#1 Unterstrasser, S., K. Gierens und P. Spichtinger: The evolution of contrail microphysics in the vortex phase, *Meteorologische Zeitschrift*, **17**, 145-156 Article